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RETRANSMISSION TECHNIQUES FOR ENHANCED PERFORMANCE IN FADING WIRELESS COMMUNICATION CHANNELS

This application claims the priority under 35 U.S.C. 119(e)(1) of copending U.S. provisional application number 60/185,780, filed on February 29, 2000.

FIELD OF THE INVENTION

The invention relates generally to wireless communications and, more particularly, to wireless communications over fading channels.

BACKGROUND OF THE INVENTION

Present telecommunication system technology includes a wide variety of wireless networking systems associated with both voice and data communications. An overview of several of these wireless networking systems is presented by Amitava Dutta-Roy, *Communications Networks for Homes*, IEEE Spectrum, pg. 26, Dec. 1999. Therein,

Dutta-Roy discusses several communication protocols in the 2.4 GHz band, including IEEE 802.11 direct-sequence spread spectrum (DSSS) and frequency-hopping (FHSS) protocols. A disadvantage of these protocols is the high overhead associated with their implementation. A less complex wireless protocol known as Shared Wireless Access Protocol (SWAP) also operates in the 2.4 GHz band. This protocol has been developed by the HomeRF Working Group and is supported by North American communications companies. The SWAP protocol uses frequency-hopping spread spectrum technology to produce a data rate of 1 Mb/sec. Another less complex protocol is named Bluetooth after a 10th century Scandinavian king who united several Danish kingdoms. This protocol also operates in the 2.4 GHz band and advantageously offers short-range wireless communication between Bluetooth devices without the need for a central network.

The Bluetooth protocol provides a 1 Mb/sec data rate with low energy consumption for battery powered devices operating in the 2.4 GHz ISM (industrial, scientific, medical) band. The current Bluetooth protocol provides a 10-meter range and an asymmetric data transfer rate of 721 kb/sec. The protocol supports a maximum of three voice channels for synchronous, CVSD-encoded transmission at 64 kb/sec. The Bluetooth protocol treats all radios as peer units except for a unique 48-bit address. At the start of any connection, the initiating unit is a temporary master. This temporary assignment, however, may change after initial communications are established. Each master may have active connections of up to seven slaves. Such a connection between a

master and one or more slaves forms a "piconet." Link management allows communication between piconets, thereby forming "scatternets." Typical Bluetooth master devices include cordless phone base stations, local area network (LAN) access points, laptop computers, or bridges to other networks. Bluetooth slave devices may include cordless handsets, cell phones, headsets, personal digital assistants, digital cameras, or computer peripherals such as printers, scanners, fax machines and other devices.

The Bluetooth protocol uses time-division duplex (TDD) to support bi-directional communication. Spread-spectrum technology or frequency diversity with frequency hopping permits operation in noisy environments and permits multiple piconets to exist in close proximity. The frequency hopping scheme permits up to 1600 hops per second over 79 1-MHZ channels or the entire ISM spectrum. Various error correcting schemes permit data packet protection by 1/3 and 2/3 rate forward error correction. Further, Bluetooth uses retransmission of packets for guaranteed reliability. These schemes help correct data errors, but at the expense of throughput.

The Bluetooth protocol is specified in detail in Specification of the Bluetooth System, Version 1.0A, July 26, 1999, which is incorporated herein by reference.

In wireless communication systems such as mentioned above, the well-known disadvantageous phenomenon of fading is encountered.

In a Bluetooth SCO (Synchronous Connection-Oriented) link, essentially used for voice communications, a packet of type HV1 can be used. This packet has 80 bits of data that are encoded using a 1/3 repetition code to produce 240 bits of coded data. In the receiver a majority decoding scheme is applied to decode the 80 bits. Since the communications link here is a wireless link and hence subject to fading, most of the errors will occur in packets subjected to severe fading.

It is therefore desirable to improve the quality of communication provided by a wireless communication channel that is subject to fading.

According to the invention, a bit sequence is transmitted over a wireless communication channel a plurality of times, and the receiving end can determine the transmitted bit sequence (1) by making a majority logic decision with respect to the received bit sequences or (2) based on the received bit sequences and corresponding quality information associated with the respective transmissions. Quality indicators associated with the respective transmissions can be compared or otherwise used in combination to determine the received bit sequence. The invention advantageously applies the effect of repetition coding across a plurality of transmissions, and thereby provides more gain in fading channels than prior art schemes.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 diagrammatically illustrates pertinent portions of exemplary embodiments of a wireless packet transmitting station according to the invention.

FIGURE 2 diagrammatically illustrates pertinent portions of exemplary embodiments of a wireless packet receiving station according to the invention.

FIGURE 3 illustrates exemplary operations which can be performed by the receiving station of FIGURE 2.

FIGURE 4 diagrammatically illustrates pertinent portions of exemplary embodiments of another wireless packet receiving station according to the invention.

FIGURE 5 illustrates exemplary operations which can be performed by the receiving station of FIGURE 4.

FIGURE 6 diagrammatically illustrates pertinent portions of exemplary embodiments of another wireless packet receiving station according to the invention.

FIGURE 7 illustrates exemplary operations which can be performed by the receiving station of FIGURE 6.

FIGURE 8 diagrammatically illustrates pertinent portions of exemplary embodiments of another wireless packet receiving station according to the invention.

FIGURE 9 illustrates exemplary operations which can be performed by the receiving station of FIGURE 8.

FIGURE 10 diagrammatically illustrates pertinent portions of exemplary embodiments of a wireless packet receiving station according to the invention.

FIGURE 11 illustrates exemplary operations which can be performed by the embodiments of FIGURE 10.

FIGURE 12 illustrates simulation results achieved according to the invention.

DETAILED DESCRIPTION

FIGURE 1 diagrammatically illustrates exemplary embodiments of a wireless packet transmitting station according to the invention. The transmitting station of FIGURE 1 transmits each packet N times (an original transmission + N-1 retransmissions). In the example of FIGURE 1, packet 1 is initially loaded into a buffer 11, and is sequentially transmitted by a wireless transmitter 13 over a wireless communications link 15 for a total of N transmissions. When the transmitter 13 has completed the Nth transmission, a signal 17 is output from the transmitter 13 in order to load the next packet, namely packet 2 into the buffer 11. Thereafter, packet 2 is transmitted N consecutive times, and the process is repeated for each packet in the packet sequence designated generally at 14. Also as shown in FIGURE 1, each retransmission of a given packet, such as packet 1, can be performed at a different transmit frequency (f1, f2 … fN) thereby advantageously achieving diversity gain. As one example, the transmitting station of FIGURE 1 can be a Bluetooth master device wherein, for example, all transmissions of packet 1 are directed to the same slave device during respective time slots of a conventional Bluetooth SCO link. As another example, the transmitting station of FIGURE 1 could be a Bluetooth slave device wherein, for example, all transmissions of packet 1 are directed to an associated master device during respective time slots of a Bluetooth SCO link.

FIGURE 10 diagrammatically illustrates pertinent portions of exemplary embodiments of a wireless packet receiving station according to the invention. The packet receiving station of FIGURE 10 includes a transmitted bit sequence determiner 100 which receives (via an unillustrated wireless communications interface) N received bit sequences which each correspond to a transmitted bit sequence that has been included in each of N packets transmitted, for example, by the transmitting station of FIGURE 1. The transmitted bit sequence determiner also receives communication quality information respectively corresponding to the N packet transmissions (and thus to the N received bit sequences). The transmitted bit sequence determiner 100 then makes a determination as to the transmitted bit sequence, based on the N received bit sequences and the corresponding communication quality information. In some embodiments the determiner 100 compares the communication quality information associated with the N received bit sequences, and thereby makes the determination of the transmitted bit sequence. In other embodiments the determiner 100 uses the communication quality information associated with the N received bit sequences to combine the N received bit sequences and thereby make the determination of the transmitted bit sequence. In still other embodiments, the determiner can include majority logic that applies a majority logic operation to the received sequences on a per bit basis. The bit-by-bit decisions of the majority logic operation constitute the determination of the transmitted bit sequence. The communication quality information is therefore not used in majority logic embodiments.

FIGURE 11 illustrates exemplary operations which can be performed by the wireless packet receiving station illustrated in FIGURE 10. At 110, the received bit sequences are produced. The communication quality information associated with the received bit sequences is obtained at 111. At 112, a determination of the transmitted bit sequence is made based on the received bit sequences and the communication quality information. The use of majority logic to produce the determination of the transmitted bit sequence is illustrated at 113.

As will be evident hereinbelow, further exemplary embodiments of the present invention, described relative to FIGURES 2-9, advantageously incorporate inventive features described above with respect to FIGURES 10 and 11.

Assume that a packet transmitted over a wireless communication link includes a predetermined bit sequence. For each bit of the transmitted sequence, if the probability of receiving that bit in error is known, then the optimal receiver can be derived from principles of information theory. In particular, the goal is to maximize the *a priori* probability of receiving the transmitted sequence correctly. Thus, the optimal receiver would be:

$$\max_{x} p(r|x) \tag{1}$$

where r represents the received bit sequence and x represents the transmitted bit sequence (r and x can each include one or more bits) and $p(r|x)$ represents the probability that the transmitted sequence x results in the received sequence r at the receiving end.

Because the respective probabilities associated with N transmissions of a packet (e.g., packet 1 in FIGURE 1) are independent, Expression 1 above can be written as follows:

$$\max_x p(r_1|x)p(r_2|x)\ldots p(r_N|x), \tag{2}$$

where r_1, r_2 … r_N represent the received sequences respectively associated with packet transmissions 1 through N. The desired transmitted sequence x is that which maximizes the product of probabilities in Expression 2.

The probabilities in Expression 2 above would generally depend on the respective signal-to-noise ratios (SNRs), after fading, of the respective packet transmissions. If the SNRs can be estimated, then the probabilities in Expression 2 can be stored in a look-up table (in a suitable memory device) indexed against SNR. These probabilities can be determined, for example, empirically based on experimentation.

FIGURE 2 diagrammatically illustrates pertinent portions of an exemplary embodiment of a wireless packet receiving station which can implement the optimal receiver represented by Expression 2 above. In FIGURE 2, a conventional receiver at 20 uses conventional techniques to receive incoming packets transmitted over the wireless communication link 15 by the packet transmitting station of FIGURE 1 A packet decoder is coupled to the receiver 20, and can use conventional techniques to decode N transmissions of a given packet. The N decoded packets, respectively including the N received sequences r_1-r_N, are stored in a buffer 22. The receiver 20 includes a SNR estimator 21 which can use conventional techniques to estimate the SNR associated with each of the N received packets. The estimated SNRs, designated SNR_1 – SNR_N, are also input to the buffer 22. The received sequences r_1-r_N and their corresponding SNR estimates SNR_1- SNR_N are input to a look-up table 23. Also input to the look-up table 23 are all possible transmitted bit sequences, designated as x(i) in FIGURE 2. If the transmitted sequence is known to be K bits long, then there are 2^K possible transmitted sequences. Thus the index i in x(i) can take integer values from 1 through 2^K, one value for each possible transmitted sequence. For each of the 2^K possible transmitted sequences represented by x(i), N corresponding probabilities are (stored in and) obtained from the look-up table 23, one probability for each of the N packets.

For example, given a received sequence such as r_1 and its associated SNR estimate SNR_1, and given a selected one of the 2^K possible transmitted sequences x(i), for

example x(4), a predetermined probability associated with the received sequence r_1 and its corresponding estimate SNR_1 and the possible transmitted sequence x(4) can be retrieved from the look-up table 23. The remaining N-1 probability values associated with x(4) correspond to r_2-r_N and their respective estimates SNR_2-SNR_N. The N probability values obtained from table 23 are multiplied by multiplier 24 to produce a product P(i) (P(4) in this example) of the N probabilities associated with the particular possible transmitted sequence x(i) (see also Expression 2). This product P(i) is stored in a buffer 25 along with products of probabilities associated with the other possible transmitted sequences x(i). Thus, the buffer 25 includes 2^K products, one for each possible transmitted sequence x(i). These 2^K products P(1)...P(2^K) in the buffer 25 are input to a maximum determiner 26 that determines which of the 2^K products is the largest, and outputs a signal 27 indicative of the largest product. This signal 27 is applied to a selector 28 to select the corresponding one of the 2^K possible transmitted sequences x(1), ... x(2^K). The sequence selected by the selector 28 is taken to be the transmitted sequence x, and can be provided for use by a communication application.

FIGURE 3 illustrates exemplary operations which can be performed by the receiving station of FIGURE 2. After a packet is received at 31, it is decoded at 32, and its associated SNR is estimated. The operations at 31 and 32 are repeated until it is determined at 33 that all transmissions of the packet have been received. Thereafter at 34 the product of probabilities P(i) is determined based on the received sequences (r_1-r_N),

their estimated SNRs (SNR_1-SNR_N), and the i th possible transmitted sequence (x(i)). As shown at 35 and 36, the operations at 34 are repeated until all of the 2^K possible transmitted sequences x(i) have been considered. Thereafter at 37, the possible transmitted sequence x(i) having the largest associated product P(i) is selected.

FIGURE 4 diagrammatically illustrates pertinent portions of a further exemplary embodiment of a wireless packet receiving station according to the invention. The packet receiving station of FIGURE 4 includes a conventional receiver 41 which can use conventional techniques to receive packets transmitted over the wireless communication link 15 by the packet transmitting station of FIGURE 1. A conventional packet decoder 42 is coupled to the receiver 41 for decoding each of the N packets received from the transmitting station. The N decoded packets, respectively including received bit sequences r_1-r_N, are stored in a buffer 44 coupled to an output of the decoder 42.

The N packets received from the transmitting station are also input to a correlator 43 coupled to the receiver 41. The correlator 43 can use conventional techniques to provide respective correlation values (e.g., maximum correlation values) for the N received packets. These correlation values, designated as α_1-α_N in FIGURE 4, are stored in a buffer 45 coupled to an output of the correlator 43. The correlator 43 can correlate with the longest known part of the received packets, for example a known header portion. In Bluetooth embodiments, the correlator can perform conventional sync word

correlation to produce the correlation values α_1-α_N. The correlation values stored in the buffer 45 are input to a maximum determiner 46 which determines the largest of the correlation values α_1 and α_N and outputs a signal 47 indicative thereof. The signal 47 controls a selector 48 appropriately to select the one of the buffered bit sequences r_1-r_N that corresponds to the largest of the correlation values α_1-α_N. The selected received bit sequence is taken to be the transmitted sequence x, and can be provided to a communication application.

The wireless packet receiving station illustrated in FIGURE 4 can be, for example, a Bluetooth packet receiving station such as a Bluetooth master device or a Bluetooth slave device. In Bluetooth embodiments, the sequence x output from the selector 48 can be produced by applying the *sign* function to the selected one of the received bit sequences r_1-r_N, that is, *sign*(selected one of bit sequences r_1-r_N).

FIGURE 5 illustrates exemplary operations which can be performed by the wireless packet receiving station of FIGURE 4. At 51-53, each of the N transmitted packets is received and decoded, and the corresponding N correlation values are obtained. Thereafter at 54, the received bit sequence that has the largest associated correlation value is selected.

FIGURE 6 diagrammatically illustrates pertinent portions of further exemplary embodiments of a wireless packet receiving station according to the invention. The

packet receiving station of FIGURE 6 can produce and buffer the received bit sequences r_1-r_N and the correlation values α_1-α_N in generally the same fashion as described above with respect to FIGURE 4. The received bit sequences r_1-r_N and the correlation values α_1-α_N are input to a combiner 61 which combines the received bit sequences and associated correlation values as follows:

$$\sum_{j=1}^{N} \left|\alpha_j\right|^2 r_j \tag{3}$$

In this combining operation, the correlation values α_1-α_N are essentially used as estimates of the fading amplitudes respectively associated with the N transmitted packets. In some embodiments, $|\alpha_j|$ can be used in Expression 3 instead of $|\alpha_j|^2$. The output of the combiner 61 is coupled to a conventional packet decoder 63, which decodes the output of combiner 61 to produce the receiving station's determination of the desired transmitted sequence x.

FIGURE 7, when considered in conjunction with FIGURE 5, illustrates exemplary operations which can be performed by the packet receiving station of FIGURE 6. As can be seen from FIGURES 5 and 7, after the N packets have been received,

decoded and correlated at 51-53 in FIGURE 5, the correlation values are combined at 71 with the received bit sequences from the corresponding decoded packets. Thereafter at 72, the result of the combining operation 71 is decoded, after which operations can return to 51 in FIGURE 5.

FIGURE 8 diagrammatically illustrates pertinent portions of further exemplary embodiments of a wireless packet receiving station according to the invention. In the packet receiving station of FIGURE 8, the correlation values α_1-α_N can be obtained and buffered in generally the same fashion as described above with respect to FIGURES 4 and 6. However, in the packet communication station of FIGURE 8, the N packets received by receiver 41, including bit sequences y_1-y_N corresponding to the transmitted bit sequence x, are buffered at 81 without decoding. The bit sequences y_1-y_N are then provided to a combiner 82 along with the correlation values α_1-α_N. The combiner 82 combines the bit sequences y_1-y_N with the correlation values α_1-α_N as follows:

$$\sum_{j=1}^{N} \left|\alpha_j\right|^2 y_j . \qquad (4)$$

In some embodiments, $|\alpha_j|$ can be used in Expression 4 instead of $|\alpha_j|^2$. The combiner 82 includes an output coupled to a conventional packet decoder 83. The packet decoder

83 decodes the output of the combiner 82, thereby producing the receiving station's determination of the desired transmitted sequence x.

FIGURE 9 illustrates exemplary operations which can be performed by the packet receiving station of FIGURE 8. At 91-93, all N packets are received, and their corresponding correlation values are obtained. Thereafter at 94, the correlation values are combined with the bit sequences received in the corresponding packets. Thereafter at 95, the result of the combining operation 94 is decoded.

The exemplary wireless packet receiving stations illustrated in FIGURES 6 and 8 can be, for example, Bluetooth master and slave devices. In such Bluetooth embodiments, the outputs of the combiners 61 and 82 can represent the *sign* function applied respectively to Expressions 3 and 4 above, namely, $sign\left(\sum_{j=1}^{N}\left|a_j\right|^2 r_j\right)$ and $sign\left(\sum_{j=1}^{N}\left|\alpha_j\right|^2 y_j\right)$.

FIGURE 12 illustrates simulation results which show examples of the performance of the embodiments of FIGURES 4 and 5 (101), the embodiments of FIGURES 6-9 (102), and majority logic embodiments (103). As shown in FIGURE 10,

the embodiments of FIGURES 4-9 generally provide 1.5 dB of gain at a bit error rate of 10^{-3}.

It will be recognized by workers in the art that the embodiments of FIGURES 1-11 can be readily implemented, for example, by suitable modifications in software, hardware, or a combination of software and hardware, in conventional wireless packet transmitting and receiving stations, for example Bluetooth master and slave devices.

Although exemplary embodiments of the invention are described above in detail, this does not limit the scope of the invention, which can be practiced in a variety of embodiments.